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Soil Quality and Water Intake in Traditional-Till vs. No-Till Paired Farms in Washington's Palouse Region

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ABSTRACT

Many farmers in the steeply sloped Palouse region of eastern Washington and northern Idaho practice no-till (NT) farming. Soil quality and water intake parameters were assessed in standing wheat (*Triticum aestivum* L.) stubble along summit, side, and toe-slope positions in a 2-yr study at three paired-farm sites using traditional tillage (TT) vs. NT management. Paired sites had similar south-facing aspect, slopes ranged from 29 to 45%, and NT fields had not been tilled from 2 to 20 yr. Soil aggregates >1000 μm were 5.4 to 9.8% higher in NT compared with TT. Soil organic carbon (SOC) in NT was 30% greater than in TT at the toe-slope position. Dehydrogenase enzyme activity (DEA) was higher in TT, mainly due to the exposed $CaCO_3$ layer at the side-slope position and higher pH of TT. Phospholipid fatty acid methyl ester (PLFA) analysis showed that fungal biomarkers were higher and Gram positive and Gram negative biomarkers were lower in NT compared with TT. There were no differences in over-winter soil water storage or ponded water infiltration rate in undisturbed standing wheat stubble between TT and NT, indicating soils that produce high wheat grain yield of 6 Mg ha^{-1} or more have similar water intake regardless of tillage history as long as the stubble is left standing over winter. Results show long-term cumulative benefits of NT vs. TT on soil quality, but no differences in soil water intake when stubble is left standing over winter, possibly due to the high quantity of wheat root channels produced in both systems.

Many farmers in the Palouse region are adopting NT practices to reduce water erosion, enhance soil quality, increase water use efficiency, and improve farm economics. The Palouse region encompasses 750000 ha of cropland that is recognized for world record grain yields of dryland winter wheat that average 6.5 to 7 Mg ha^{-1}. Tillage is generally intensive, with the moldboard plow historically used to completely invert the top 15 to 25 cm of soil to bury winter wheat stubble to prepare a seedbed. Water erosion rates following moldboard plowing used in past years averaged 45 Mg soil loss ha^{-1} yr^{-1} (USDA, 1978). Presently, more than 40% of Palouse cropland is under conservation tillage and water erosion rates are reduced from previous (USDA, 1978) levels, but still exceed the tolerable rate of 11 Mg ha^{-1} yr^{-1} in some areas (Renard et al., 1997). Approximately 5% of dryland crop hectares in the western USA are planted using NT (CTIC, 2002).

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The Palouse region receives an average of 420-to 600-mm annual precipitation with the majority occurring during the winter. Farming is performed on 8 to 45% slopes on deep loessial soils. The land was broken out of native prairie grassland for farming only 125 yr ago, but SOC has declined to half the original values of the native soil during that time (Papendick et al., 1985). Reduction or elimination of tillage will slow or halt the rate of SOC loss and is critical in the development of successful conservation tillage systems (Papendick and Parr, 1997). Research on conservation tillage and cropping systems is needed to improve soil quality, maximize over-winter soil water storage, and reduce water erosion. Potential for economic and environmental benefits is a major driving force in the ongoing gradual shift by farmers to adopt reduced- and no-till farming methods.

Surface residue retention and the amount of soil disturbance are key factors in choosing management systems. Surface residue improves soil quality (Doran et al., 1996) by increasing SOC accumulation (Nyakatawa et al., 2001), fungal biomass, earthworm populations, and DEA (Holland and Coleman, 1987; Karlen et al., 1994). Changes in the soil ecology that occur with NT are dependent on many factors, such as landscape position, soil type and depth, precipitation, temperature, and residue management.

Due to high residue levels and steep slopes, farmers in the Palouse region have lagged behind other areas of the USA and the world (i.e., Argentina, Brazil, and Canada) in adopting NT. The main collaborators for the study, John and Cory Aeschliman of Colfax, WA, have been leaders in the NT farming movement in the PNW for more than 20 yr (Mallory et al., 1999). The Aeschlimans have adopted NT on their family owned land and, in recent years, on land that they lease. Thus, parcels of the Aeschliman farm have been in continuous NT from 2 to 20 yr. These fields with various years into NT provided an avenue to study changes with NT compared with TT over time.

In the PNW, residue burial with tillage during the fall reduces over-winter soil water storage compared with leaving stubble standing over the winter (Papendick and McCool, 1994). One of our goals was to measure the long-term cumulative effects of TT vs. NT on over-winter soil water storage and ponded water infiltration rate, thus tillage was conducted in the spring in this study. Our hypothesis for the experiment was that, as the time in NT

Abbreviations: AD, soil aggregate distribution; D_b, bulk density; DEA, dehydrogenase enzyme activity; EC, electrical conductivity; FAME, fatty acid methyl esters; NT, no-till; SOC, soil organic carbon; OWS, over-winter soil water storage; PCA, principal component analysis; PLFA, phospholipid fatty acid methyl esters; PNW, Pacific Northwest; POM, particulate organic matter; PWI, ponded water infiltration rate; TT, traditional tillage.

increased, soil quality indicators would improve and greater over-winter soil water storage and ponded water infiltration rate would occur. The objective was to assess soil quality parameters, over-winter soil water storage, and ponded water infiltration rate across slope positions under TT vs. NT management on three paired farms.

MATERIALS AND METHODS

Field Layout

A 2-yr field experiment was conducted on three paired farms located between the towns of LaCrosse and Colfax in Whitman County, WA to compare TT vs. NT management practices. The NT fields had been in continuous NT from 2 to 20 yr. The NT portion of Site 1 had been in NT for 2 yr, Site 2 for 7 yr, and Site 3 for 20 yr (Table 1). The actual fields used were different each year to ensure paired fields of standing wheat stubble.

Experimental design was a split plot with three paired farms used as replicates. Traditional-till and NT were whole-plot treatments at each paired farm. Three slope positions (summit, side, and toe) were subplots. Measurements from the summit and toe slope were obtained 10 m below and above the true summit and toe, respectively, as these represented the large land areas typically associated with these slope positions. Side slope measurements were obtained from the middle of the slope. Soil properties, over-winter soil water storage, and ponded water infiltration rate measurements were obtained within a 1-wk period in September and April during both years at all three slope positions at all paired sites. All sites were south-facing with slopes ranging from 29 to 45%. Slopes at each of the paired sites were roughly equivalent (Table 1) and slope length ranged from 100 to 250 m. The TT and NT components of each paired farm were located within 1 km of each other. Soil at Site 1 was Athena silt loam (fine-silty, mixed, superactive, mesic Pachic Haploxerolls) and soil at Sites 2 and 3 was Palouse silt loam (fine-silty, mixed, superactive, mesic Pachic Ultic Haploxerolls). Average annual precipitation at the sites ranged from 420 to 480 mm with precipitation increasing from west to east, that is, from Site 1 to Site 3. Sites were characterized by a petrocalcic horizon exposed only at the side-slope position (Busacca and Montgomery, 1992). General soil characteristics of texture (Gee and Or, 2002), N and S (LECO CNS analyzer, LECO, St. Joseph, MI), available P (Fixen and Grove, 1990) and K (Haby et al., 1990), and cation exchange capacity (Sumner and Miller, 1996) were determined on soil sampled at the start of the study (Table 1).

An analysis of variance for all data was conducted using the mixed model procedure of SAS (SAS Institute, 1999). Treatment means were considered significantly different at $P < 0.05$ using Fisher's protected least significant difference.

Crop Rotations and Field Operations

Crop rotations for TT and NT at all paired sites are shown in Table 1. Crop rotation for TT at Sites 1 and 2 was winter wheat– summer fallow, where only one crop is grown every other year. At Site 3, the TT crop rotation was winter wheat–spring wheat. At all NT sites, the crop rotation was spring wheat–chemical summer fallow–winter wheat, although spring barley (*Hordeum vulgare* L.) was periodically substituted for spring wheat in this 3-yr rotation in years before the study. For both TT and NT at all paired sites, the standard practices of the growers were used. Wheat stubble was left standing and undisturbed from grain harvest in August until April of the following year. An average 67 kg N ha^{-1} and 15 kg P ha^{-1} was supplied to each cereal crop each year as fertilizer (Halvorson et al., 1986; Mahler and Guy, 1998).

Table 1. Characteristics of three paired farm sites near Colfax, WA where traditional-till (TT) and no-till (NT) management systems were compared. All soil physical, chemical, and water measurements were taken in undisturbed standing winter wheat stubble, except for NT in 2000–2001 at Site 3 and NT in 2001–2002 at Sites 1 and 2, where measurements were taken in undisturbed standing spring wheat stubble.

Site			Units	1	2	3
Soil type				Athena silt loam	Palouse silt loam	Palouse silt loam
Average annual precipitation			mm	420	420	480
Soil texture			% Sand	9.0	13.0	13.0
			% Silt	75.7	69.8	69.8
			% Clay	15.3	18.2	18.2
Slope	Yr 1	TT	%	29	45	32
	Yr 1	NT	%	32	44	39
	Yr 2	TT	%	31	41	33
	Yr 2	NT	%	30	40	34
N		TT	μg N g soil^{-1}	0.12	0.14	0.14
		NT		0.13	0.13	0.14
S		TT	μg S g soil^{-1}	0.011	0.012	0.011
		NT		0.012	0.011	0.011
P		TT	μg P g soil^{-1}	5.1	5.0	3.5
		NT		9.0	10.0	11.0
K		TT	μg K g soil^{-1}	250	200	100
		NT		200	250	480
Cation exchange capacity		TT	cmol (+) kg soil^{-1}	22	22	20
		NT		24	22	20
Year in NT			Years	2	7	20
Crop rotation		TT		Winter wheat–summer fallow	Winter wheat–summer fallow	Winter wheat–spring wheat
		NT		Spring wheat–chemical summer fallow–winter wheat	Spring wheat–chemical summer fallow–winter wheat	Spring wheat–chemical summer fallow–winter wheat

The standard field practices for TT at all three sites for at least a decade before the study were: (i) application of 0.32 kg a.e. (acid equivalent) ha^{-1} glyphosate herbicide [N-(phosphonomethyl) glycine] in March to control weeds; (ii) primary spring tillage at a depth of 12 cm in April using a tandem disk with 55-cm-diameter blades; (iii) inject aqua NH_3–N fertilizer with shanks spaced 30-cm apart in April, and; (iv) tillage with a duck-foot cultivator at a depth of 8 cm with attached spike-tooth harrow in late April or early May. At Sites 1 and 2, an average of three rodweeding (a 1-cm square rotating rod) operations was conducted at a depth of 7 cm between May and August to control weeds in summer fallow. At Site 3, in lieu of summer fallow, spring wheat was planted in early May with a double-disk drill.

No-till management at all sites during all years first received an application of 0.32 kg a.e. ha^{-1} glyphosate herbicide 2 to 3 wk before planting. Fields were planted and fertilized in one pass through the standing winter wheat or spring wheat stubble with either a Yielder (Yielder Co., Spokane, WA) or Great Plains NT disk-type drill (Great Plains Manufacturing, Salina, KS) in late April or early May.

All measurements were taken within a 1-wk period in September and April in undisturbed standing winter wheat stubble, except for NT in 2000–2001 at Site 3 and NT in 2001–2002 at Sites 1 and 2, where measurements were taken in undisturbed standing spring wheat stubble.

For laboratory analysis of soil physical, chemical, and biological properties, soil samples were obtained from 0- to 5- and 5- to 10-cm depths at the summit, side, and toe-slope positions in all sites in September 2000, April 2001, and April 2002. Five soil samples at each slope position, each a composite of seven cores, were taken randomly across the slope position with a 5-cm diam. soil sampling tube. Samples for aggregate distribution were taken from the 0- to 5-cm depth only with a 10-cm diam. golf hole cutter.

Soil Analysis—Physical

Aggregate-size distribution was determined on oven-dried soil cores by placing 600 g of intact soil core on top of nested sieves of 1000, 500, 250, and 53 μm. The soil and sieves were shaken on a rotary sieve shaker (Tyler Sieve Co., Mentor, OH) for 45 min at 280 oscillations min^{-1} (Nimmo and Perkins, 2002). The soil remaining on the top of each sieve and in the bottom pan was weighed and percentages in each fraction calculated. This aggregate distribution procedure was chosen for these soils as it gave more reproducible results with similar distribution of aggregates when compared with using a smaller sample size and less shaking time. Bulk density (D_b) was determined as described by Doran and Mielke (1984) on five 10-cm diameter intact oven-dried soil cores obtained in April before tillage and/or planting at 0- to 10-cm depth.

Soil Analysis—Chemical

The pH and electrical conductivity (EC) were determined by preparing a 1:1 slurry (10 g soil + 10 mL deionized H_2O) and allowing them to reach equilibrium at room temperature (Smith and Doran, 1996). The pH was determined with an Orion Research 811 (Boston, MA) pH meter. Electrical conductivity was measured using a digital conductivity meter (VWR International, Bristol, CT). Total soil C was determined with a LECO CNS analyzer (LECO, St. Joseph, MI) using air-dried and ground (to pass a 1-mm sieve) soil. SOC was determined by titrating soil to 7.0 pH to neutralize the carbonates before LECO analysis. Additionally carbonates were determined (El Mahi et al., 1987) and SOC calculated by subtraction from total C values to confirm the titration method. Particulate organic matter (POM, Cambardella and Elliott, 1992) was determined on soil samples obtained in April 2002.

Soil Analysis—Biological

Dehydrogenase enzyme activity as described by Tabatabai (1994) was used to determine microbial activity based on the reduction of triphenyl tetrazolium chloride to triphenyl formazan. Two hundred microliters of each sample were placed into microtiter plates, and absorbance read at 495 nm using a Bio-Rad model 2550 microplate reader (Hercules, CA).

Whole-soil fatty acid methyl esters (FAME) were extracted from 1-g soil samples to characterize the soil biological community. Fatty acid methyl esters analysis was conducted based on saponification of soil at 100°C, acid methylation at 80°C, an alkaline wash, and an extraction of methyl esters of long-chain fatty acids and similar lipid compounds into hexane (Ibekwe and Kennedy, 1999).

Phospholipid fatty acid methyl esters were determined on select 2002 soil samples to differentiate groups of soil microorganisms (Petersen et al., 2002). The PLFA were prepared as described by Petersen and Klug (1994) with 2 g of soil extracted by a modified Bligh-Dyer single-phase extraction. The extract was separated into an organic and an aqueous phase, and polar lipids (mainly phospholipids) in the organic phase isolated by solid phase extraction using silicic acid columns (100 mg, Varian, Harbor City, CA). Ester-linked PLFA were trans-methylated under mildly alkaline conditions.

Nonadecanoic acid methyl ester was included after the methylation step for both FAME and PLFA to enable quantification of identified lipids on a molar basis. Samples were analyzed on a gas chromatograph (Agilent Technologies GC 6890, Palo Alto, CA) with a fused silica column and equipped with a flame ionizer detector and integrator. ChemStation (Agilent Technologies GC 6890, Palo Alto, CA) operated the sampling, analysis, and integration of the samples. Peak identification and integration of areas were performed under the Eukary method parameters by software supplied by Microbial Identification Systems, Inc. (Newark, DE). Raw percentages of each fatty acid in each sample covered a wide range of values and were log transformed before using the covariance matrix of principal component analysis (PCA) in SAS (SAS Institute, 1999). The PCA explains the variance-covariance structure through a few linear combinations of the original variance with coefficients equal to the eigenvectors of the correlation matrix (Jolliffe, 1986).

Over-winter Precipitation Storage Efficiency

Soil volumetric water content was measured to a depth of 180 cm at the summit, side, and toe-slope positions in all sites after grain harvest in early September of 2000 and 2001 and again in early April of 2001 and 2002. Soil volumetric water content in the 30- to 180-cm depth was measured in 15-cm increments to a depth of 180 cm by neutron thermalization (Hignett and Evett, 2002). Water content in the 0- to 30-cm depth was determined from two 15-cm core samples using gravimetric procedures (Topp and Ferre, 2002). Three soil water measurements were always taken at each slope position in all fields.

Ponded Water Infiltration

Water infiltration at all sites and slope positions was measured with a 76-cm-diameter single-ring infiltrometer in September 2001 using procedures described by Reynolds et al. (2002). The sharp outside beveled cutting edge of the infiltrometer was driven into the soil to a depth of 5 cm with a hard-rubber hammer without disturbing the soil or standing wheat stubble within the ring. A float valve fitted inside the measuring ring was connected via flexible tubing to a gravity-fed water reservoir to maintain a constant depth of ponded water. An average depth of 8 cm of ponded water was maintained in the measuring ring, although water depth was, naturally, greatest in the down-slope portion of the ring. The steepness of slopes for TT and NT sites was similar at all paired sites during both years (Table 1). The entire soil surface within the infiltrometer ring was completely covered with ponded water throughout the procedure. Rate of water infiltration was recorded at 10-min intervals for 120 min by measuring the decline of water level in the graduated water-storage reservoir.

RESULTS

Soil Physical and Chemical Properties

Aggregate sizes above 1000 μm were higher in NT compared with TT (Table 2). The fraction <1000 μm and >500 μm was similar for NT and TT for most sites except Site 1 where NT was great than TT (Table 2). In general, the TT soils had the greater proportion of smaller (<250 μm) dry aggregate sizes found in the top 10 cm of soil compared with NT. There was a significant tillage by site interaction for aggregate-size distribution (AD) (Table 3) with the distribution of soil found in the smaller sized aggregates differing with site. The toe slope at Site 2 had two sieve sizes (53 μm; <53 μm) that were not statistically different between tillage treatments. Over all locations, AD of TT was greater than NT for the smaller size fractions.

Soil bulk density varied with slope position and tillage treatment, with site means ranging from 1.12 Mg m^{-3} in the surface 0 to 5 cm to 1.49 Mg m^{-3} in the 5- to 10-cm depth (Table 4). Bulk density of the 0- to 5-cm depth was greater for NT for means at all slope positions and slope positions at Site 1 and 2 except for the side slope at Site 2. Mean D_b values of the 5- to 10-cm depth were greater for NT for side and toe slopes. For individual sites, bulk density was statistically significant only at the side- and toe-slope position for Site 1. There was a slope by tillage interaction (Table 3) with summit positions in NT having higher D_b than any other sample.

The pH in the 0- to 5-cm depth averaged 5.80 for NT and 6.82 for TT averaged across sites and slope positions (Table 4). A petrocalcic horizon of $CaCO_3$ at the side-slope position resulted in higher pH values in TT at both the 0- to 5- and 5- to 10-cm depths when compared with NT (Table 4). Only at Site 3 (20 yr in NT) did NT and TT have similar pH. Interactions were apparent for pH for all interactions except site × slope (Table 3).

Soil EC ranged from 0.90 to 1.52 dS m^{-1}. Mean EC values for NT and TT were 1.44 and 1.25 dS m^{-1}, respectively (Table 4). At the summit position, EC values for TT at the 5- to 10-cm depth were the lowest in the study. There were no differences in EC between the two tillage treatments at Site 3, which had been in NT the longest. A significant sampling time × slope interaction was evident with changes occurring over time at the mid-slope position.

Soil organic C values ranged from 7.4 to 16.7 g C kg^{-1} (Fig. 1). Carbonates were evident for all soils with pH > 7.5. No-till had greater SOC at 0- to 5-cm depth for toe- and side-slope positions than did TT at all sites (Fig. 1a). Soil organic C was greater in NT than TT at the 5- to 10-cm depth for some, but not all, of the sampling locations. Traditional-till and NT soils had similar SOC at 0- to 5-cm depth at the summit (Fig. 1a). Significant interactions were evident for all combinations (Table 3). Tillage and landscape position did not affect the POM fraction in this study (data not shown). Even though D_b varied with treatment, SOC calculated on a per volume

Table 2. Soil aggregate distribution (%) from three slope positions (summit, side, and toe) at three paired farms under traditional-till (TT) vs. no-till (NT) management.†

Slope position	Site	Tillage	Aggregate distribution, %					
			>2000 μm	2000–1000 μm	1000–500 μm	500–250 μm	250–53 μm	<53 μm
Summit	1	TT	9.0 c†	16.8 c	14.9 c	14.4 b	29.7 a	15.1 b
	1	NT	14.7 b	29.4 ab	17.6 b	12.1 c	15.1 c	11.1 c
	2	TT	18.9 a	25.1 b	24.0 a	10.8 c	13.3 cd	7.9 d
	2	NT	20.5 a	31.1 a	20.1 b	11.1 c	10.3 d	6.9 d
	3	TT	5.8 d	15.3 c	17.4 b	14.3 b	28.7 ab	18.2 a
	3	NT	10.1 c	14.4 c	18.8 b	17.2 a	25.3 b	14.3 b
	Mean	TT	11.2 C	19.1 B	18.8 B	13.2 B	23.9 A	13.7 A
	Mean	NT	15.1 B	25.0 A	18.8 B	13.4 B	16.9 BC	10.8 B
Side	1	TT	4.5 d	10.1 d	19.0 c	16.1 b	33.4 a	16.8 a
	1	NT	22.0 a	27.6 ab	17.9 b	12.0 c	12.4 cd	8.0 d
	2	TT	19.5 a	25.0 b	22.9 a	10.8 c	12.1 d	7.6 d
	2	NT	21.9 a	19.5 c	22.0 a	12.4 c	14.6 bc	11.6 c
	3	TT	15.3 b	18.9 b	21.8 a	18.8 a	16.0 bc	14.2 b
	3	NT	8.2 c	30.0 a	21.1 ab	15.8 b	17.0 b	11.7 c
	Mean	TT	13.1 B	18.0 B	21.2 B	15.2 B	20.5 B	12.9 A
	Mean	NT	17.4 A	25.7 A	20.3 B	13.4 B	14.7 C	10.4 BC
Toe	1	TT	4.1 e	12.5 e	22.4 c	18.3 a	28.5 a	14.2 a
	1	NT	15.7 c	29.6 b	26.5 b	10.4 c	9.9 d	8.0 b
	2	TT	22.5 a	20.1 c	22.6 c	17.0 a	10.6 d	7.2 b
	2	NT	19.7 b	35.8 a	21.3 c	8.6 c	8.2 d	6.3 b
	3	TT	3.8 e	15.2 d	32.0 a	16.4 ab	19.3 b	13.3 a
	3	NT	4.4 d	18.9 cd	31.0 a	15.0 b	14.5 c	13.5 a
	Mean	TT	10.1 C	15.9 B	25.7 A	17.2 A	19.5 B	11.6 AB
	Mean	NT	13.3 AB	28.1 A	26.2 A	11.3 C	10.9 D	9.3 C

† Within-column means for each slope position across sites followed by the same lowercase letter are not significantly different at $P < 0.05$. Within-column means followed by the same uppercase letter are not significantly different at $P < 0.05$.

Table 3. Analysis of variance for over-winter precipitation storage efficiency (OWS), ponded water infiltration rate (PWI), soil aggregate distribution (AD), soil bulk density (D_b), soil pH, electrical conductivity (EC), soil organic carbon (SOC), and dehydrogenase enzyme activity (DEA). Data are from three slope positions (summit, side, and toe) on three paired farms using no-till vs. traditional-till management for two sample times each year for 2 yr.

		Source									
		Sampling Time (Y)	Slope (Sl)	Tillage (T)	Site (S)	Y × Sl	Y × T	S × T	S × Sl	T × Sl	S × T × Sl
Soil analyses	Df	2	2	1	2	4	2	2	4	2	4
AD	Sig.	NS†	*	***	***	NS	NS	***	NS	NS	NS
D_b		NS	*	*	NS	NS	NS	NS	NS	*	NS
PH		*	***	***	**	***	***	***	NS	***	***
EC		NS	NS	**	NS	*	NS	NS	NS	NS	NS
SOC		**	**	***	**	***	**	***	**	***	*
DEA		***	***	***	NS	**	***	*	***	***	***
Soil water											
OWS	Df	1	2	1	2	2	1	2	4	2	4
	Sig.	***	*	NS	*	NS	NS	NS	NS	NS	NS
PWI	Df	NA‡	2	1	2	NA	NA	2	4	2	4
	Sig.	NA	NS	NS	NS	NA	NA	NS	NS	NS	NS

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† NS = not significant.
‡ not applicable (NA) as PWI was measured only during 1 yr, therefore there are no df for yr.

basis did not yield differences in relationships among treatments at either depth.

Soil Biological Properties

Microbial activity, measured as DEA, was stimulated in TT due to the exposed calcium carbonate layer and higher pH (Table 4). Microbial activity was greatest in TT soils, especially at the side-slope position. For all three sampling dates at all slope positions, DEA in TT was greater than that found in NT at both 0- to 5- and 5- to 10-cm depths. Microbial activity was lowest in summit soils at the 0- to 5-cm depth. Dehydrogenase values were less in the 5- to 10-cm depth than in the 0- to 5-cm depth. Site differences were not evident for dehydrogenase activity. Interactions were evident for site × tillage and for sampling time × slope. All dehydrogenase activity-related interactions were significant (Table 3). The relationships among treatments were identical for DEA whether calculated on per mass or per volume basis, even though D_b differed with treatment.

Principal component analysis of whole soil FAME differentiated TT and NT soils at the side- and toe-slope positions (Fig. 2). The FAME profiles from the summit NT at all sites and all slope positions of the youngest (i.e., 2 yr) NT site were similar to TT. Tillage treatments separated on both the x and y axes due to a greater fungal component in NT. No-till soils tended to separate to the left and above TT. The first two principal components explained 40% of the variance (Fig. 2). The TT FAME fingerprints were more variable than those from NT. Analysis of peaks and biomarkers did not show any direct plant-biomarker changes with tillage method. The microbial communities at Sites 1 and 2 were similar to each other whereas Site 3 tended to cluster below Sites 1 and 2 on PC 2 when TT and NT were combined (Fig. 2). Slope position played a role in the microbial community structure; TT soils from side-slope and toe-slope positions separated more clearly below NT soils than from TT soils from the summit position. While the separation of the FAME profiles could be attributed mostly to peaks that might be considered fungal biomarkers, a more definitive characterization was needed, thus we also conducted PLFA analysis on the soils. The PLFA analysis differentiated NT from TT soils (Table 5); however, the distinction among slope position, while still present, was not as great as that seen with FAME (data not shown). Fungal biomarkers (18:1ω9c, 18:2ω6, 18:3ω6) were greater in NT soils whereas most biomarkers for both Gram positive and Gram negative bacteria (15:0 anteiso; 17:0; 19:0) were higher in TT soils.

Soil Water

There were no differences in over-winter soil water storage between TT and NT at any of the paired sites during either sampling time or when combined across sampling time (Table 3). Throughout the 180-cm profile at all sites and slope positions, over-winter water gain was closely correlated with baseline (i.e., early September) water content (Fig. 3). Over-winter water storage was significantly affected by slope position (Table 3) and the trend was in the order of summit (Fig. 3A, 3D, and 3G) < side slope (Fig. 3B, 3E, and 3H) < toe slope (Fig. 3C, 3F, and 3I). The highest over-winter soil water storage at the toe slope (Fig. 3C, 3F, and 3I) was presumably due, at least in part, to gravity flow of water. The over-winter soil water storage at the side slope and toe slope was 5 and 11% greater, respectively, than at the summit. There were significant over-winter soil water storage differences between sampling time and among sites (Table 3), but these were due to differences in the quantity of precipitation (data not shown) received between sampling time and among sites and not due to tillage treatment. There were no interactions for over-winter soil water storage-related data (Table 3). There were no differences nor were there any interactions in total quantity of ponded water that infiltrated into the soil during 120-min runs as affected by slope position, tillage, or site (Table 3). Initial ponded water infiltration rate during the first 10 min ranged from 1 to 4 mm min^{-1} at Site 1 (Fig. 4A, 4B, and 4C), 1 to 6 mm min^{-1} at Site 2 (Fig. 4D, 4E, 4F), and 4 to 10 mm min^{-1} at Site 3 (Fig. 4G, 4H, and

Table 4. Soil bulk density, pH, electrical conductivity, and dehydrogenase enzyme activity from three slope positions (summit, side, toe) at three paired farms under traditional-till (TT) vs. no-till (NT) management.†

Slope position	Site	Tillage	Bulk density, Mg m^{-3}	pH	Electrical conductivity, dS m^{-1}	Dehydrogenase enzyme activity, µg TPF cm^{-3} h^{-1}
			0 to 5 cm			
Summit	1	TT	1.20 c†	6.61 a	1.24 c	3.44 b
	1	NT	1.34 b	5.90 b	1.60 a	3.26 b
	2	TT	1.30 b	5.99 b	1.03 d	3.92 a
	2	NT	1.39 a	5.36 c	1.45 ab	3.81 ab
	3	TT	1.19 c	5.68 bc	1.26 c	4.13 a
	3	NT	1.22 c	5.45 c	1.31 bc	4.07 a
	Mean	TT	1.23 B	6.09 C	1.18 B	3.83 D
	Mean	NT	1.32 A	5.57 D	1.45 A	3.73 D
Side	1	TT	1.12 c	7.58 a	1.40 b	5.17 b
	1	NT	1.32 a	7.15 a	1.79 a	4.35 cd
	2	TT	1.41 a	7.23 a	1.14 b	5.39 b
	2	NT	1.36 a	5.38 b	1.49 ab	3.99 d
	3	TT	1.24 b	7.79 a	1.22 b	7.77 a
	3	NT	1.23 b	5.78 b	1.29 b	2.87 e
	Mean	TT	1.25 B	7.53 A	1.26 B	6.11 A
	Mean	NT	1.30 A	6.11 C	1.52 A	3.72 D
Toe	1	TT	1.31 c	6.90 a	1.27 b	6.00 a
	1	NT	1.37 b	5.97 b	1.33 b	5.26 a
	2	TT	1.31 c	7.08 a	1.34 b	5.72 a
	2	NT	1.49 a	5.37 c	1.61 a	4.09 b
	3	TT	1.28 cd	6.56 a	1.35 b	3.53 b
	3	NT	1.26 d	5.80 bc	1.38 b	4.11 b
	Mean	TT	1.24 B	6.84 B	1.32 AB	5.08 B
	Mean	NT	1.34 A	5.71 D	1.44 A	4.49 C
			5 to 10 cm			
Summit	1	TT	1.35 a	6.49 a	0.95 b	1.83 cd
	1	NT	1.38 a	5.78 b	1.56 a	1.51 d
	2	TT	1.35 a	5.71 b	0.66 c	2.41 b
	2	NT	1.38 a	5.24 c	1.48 a	1.99 c
	3	TT	1.32 b	5.45 bc	1.08 b	2.96 a
	3	NT	1.30 b	5.42 bc	1.12 b	1.79 cd
	Mean	TT	1.34 B	5.88 C	0.90 C	2.40 C
	Mean	NT	1.35 B	5.47 D	1.38 A	1.76 D
Side	1	TT	1.29 b	7.38 b	1.22 b	2.93 b
	1	NT	1.37a	7.26 b	1.85 a	2.98 b
	2	TT	1.40 a	7.38 b	1.10 b	3.39 b
	2	NT	1.39 a	5.26 c	1.34 b	2.21 c
	3	TT	1.27 b	7.87 a	1.12 b	6.29 a
	3	NT	1.30 b	5.60 c	1.11 b	1.76 c
	Mean	TT	1.32 C	7.54 A	1.14 B	4.20 A
	Mean	NT	1.35 B	6.04 C	1.43 A	2.32 C
Toe	1	TT	1.30 b	6.84 ab	1.16 ab	4.33 a
	1	NT	1.39 a	5.76 c	1.27 ab	3.05 b
	2	TT	1.38 a	7.05 a	1.23 ab	3.79 c
	2	NT	1.40 a	5.08 d	1.38 a	1.81 c
	3	TT	1.35 b	6.50 b	1.23 ab	3.28 b
	3	NT	1.32 b	5.59 cd	1.16 ab	1.89 c
	Mean	TT	1.34 B	6.80 B	1.21 B	3.79 B
	Mean	NT	1.37 A	5.47 D	1.27 AB	2.25 C

† Within-column means for each slope position across sites for each sampling depth followed by the same lowercase letter are not significantly different at $P < 0.05$. Within-column means for each sampling depth followed by the same uppercase letter are not significantly different at $P < 0.05$.

4I). Steady state ponded water infiltration rate ranged from <1 mm min^{-1} (Fig. 4B, 4C, 4E, and 4F) to >3 mm min^{-1} (Fig. 4G), and there was no consistent trend in ponded water infiltration rate between TT and NT.

DISCUSSION

Soil quality is defined as 'the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health' (Doran and Parkin, 1994). Soil quality assessments can be used to determine the effect of management practices on soil processes. Although the literature illustrates that NT and surface residue retention improves soil quality characteristics (Dalal et al., 1991; Doran et al., 1996), this may not always be the case and pest or soil management concerns may arise (Pierce et al., 1994; Kettler et al., 2000). It is imperative that site characteristics and several soil properties are measured to illustrate the effect that change in management practices may have on soil quality. Soil quality is correlated with numerous and interrelated physical, chemical, and biological parameters, not a single factor.

Soil properties in this study varied with site, landscape, and tillage system. No-till had a greater quantity of soil in the larger size aggregates compared with TT; this being consistent with the literature (Hussain et al., 1999; Wright and Hons, 2004). The greater volume of soil in the larger-

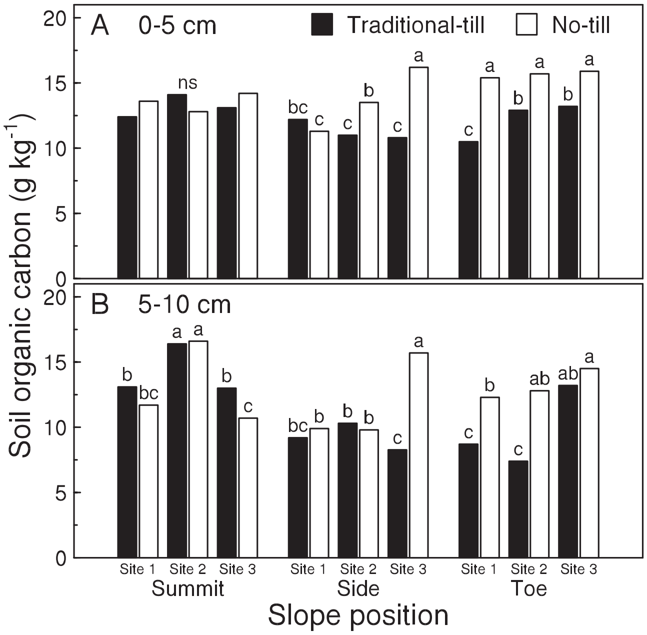

Fig. 1. Soil organic C in traditional till (TT) vs. no-till (NT) soil at (A) the 0- to 5-cm and (B) 5- to 10-cm soil depths at three slope positions. Data are means across sites and years.

size aggregates may protect the NT soil from wind and water erosion. Soil D_b was greater in the NT soils (Table 4). This higher D_b is in agreement with studies that have found greater D_b with long-term no-till (Hammel, 1989; Pierce et al., 1994), but in contrast to some no-till/tilled soil comparisons in which the surface layers of NT had lower D_b (Kettler et al., 2000; Edwards et al., 1992). Bulk density at the 5- to 10-cm depth was also often higher in NT than TT, but significantly different only for mean values and at Site 1, the youngest site at side and toe slope. This may be indicative of a compaction layer occurring within the depth of soil we sampled in NT.

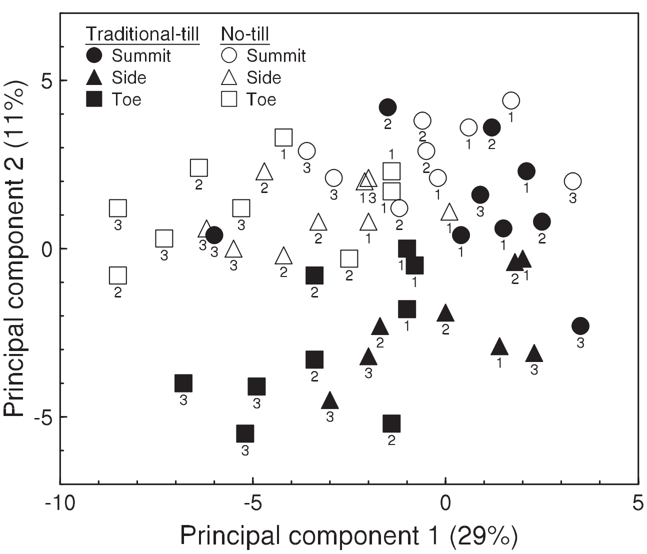

Fig. 2. Principal component analysis (PCA) of whole-soil FAME for traditional till (TT) and no-till (NT) soils at summit-, side-, and toe-slope positions. Data are means across sites and years. Numbers below symbols indicate the site where the soil sample was obtained.

Table 5. Phospholipid fatty acid content (%) for the 0- to 5-cm depth under traditional-till (TT) vs. no-till (NT) management from three paired farms.†

Fatty acid	Group of organisms	TT	NT
		%	
11:0 iso	Gram positive bacteria	0 b	0.17 a
15:0 anteiso	Gram positive bacteria	2.75 a	2.48 b
16:1 ω7c	Gram negative bacteria	4.50 a	4.62 a
17:0 anteiso	Gram positive bacteria	1.06 a	0.75 b
17:0 cyclo	Gram negative bacteria	1.45 a	0.98 b
18:1 ω9c	Fungi	6.07 b	6.92 a
18:2 ω6c	Fungi	4.38 b	6.44 a
18:3 ω6c	Fungi	0.96 b	1.33 a
19:0 cyclo	Gram negative bacteria	0.84 a	0.27 b

† Within-row means for each tillage treatment across sites followed by the same letter are not significantly different at $P < 0.05$.

The pH and DEA were greater in TT soils. While EC differed between the two tillage systems at 5 to 10 cm, these differences were probably due to fluxes from fertilizer and salts. Differences in EC values were not large enough to indicate biologically important changes as all EC values were 1.5 dS m^{-1} or less. The greatest differences between tillage treatments occurred at the summit position. A calcium carbonate layer was evident at the side-slope position, which increased pH and DEA of TT. The Palouse landscape is one of gently rolling hills of windblown dust called loess. Since the time when the petrocalcic horizon was formed, deposition of dust and water erosion have changed the topography (Busacca and Montgomery, 1992) such that the petrocalcic horizon now crops out at irregular depths on the landscape, thus exposing this $CaCO_3$ layer at side-slope position, but not at toe- or summit-slope positions. With TT, $CaCO_3$ was mixed by tillage that raised the pH in this layer, which in turn affected the DEA. The dispersal of $CaCO_3$ was much less in NT soils as evidenced by the lower pH, especially in the summit- and toe-slope positions. Tillage may have also affected pH by stratifying soil properties and fertilizer similar to results reported in a 20-yr study of tillage practices in Australia (Dalal et al., 1991) where pH was lower in NT compared with TT.

The greatest benefit of NT was higher SOC levels than that found in TT (Fig. 1), which is similar to results from many other long-term tillage studies (Dalal et al., 1991; Nyakatawa et al., 2001). Little difference in SOC was seen at the summit between TT and NT. Results show that SOC, C, N, pH, and exchangeable bases vary with land use and are similar to findings from other soil quality studies conducted in the Pacific Northwest (Brejda et al., 2002).

In a previous study at Site 3 (Kennedy and Smith, 1995), microbial diversity was greater in TT compared with NT where tillage mixed the soil and made more substrate available or increased the stress slightly. The calcium carbonate layer in that study (Kennedy and Smith, 1995), as in this study, resulted in higher pH in the TT treatment. These higher pH values would lead to increased DEA due to the suppressive effects of low pH on bacterial growth (Baath, 1998). In this study, tillage altered the composition of the microbial communities as seen by FAME. We found an increase in the fungal component with NT as determined by PLFA analysis. A similar increase in fungal

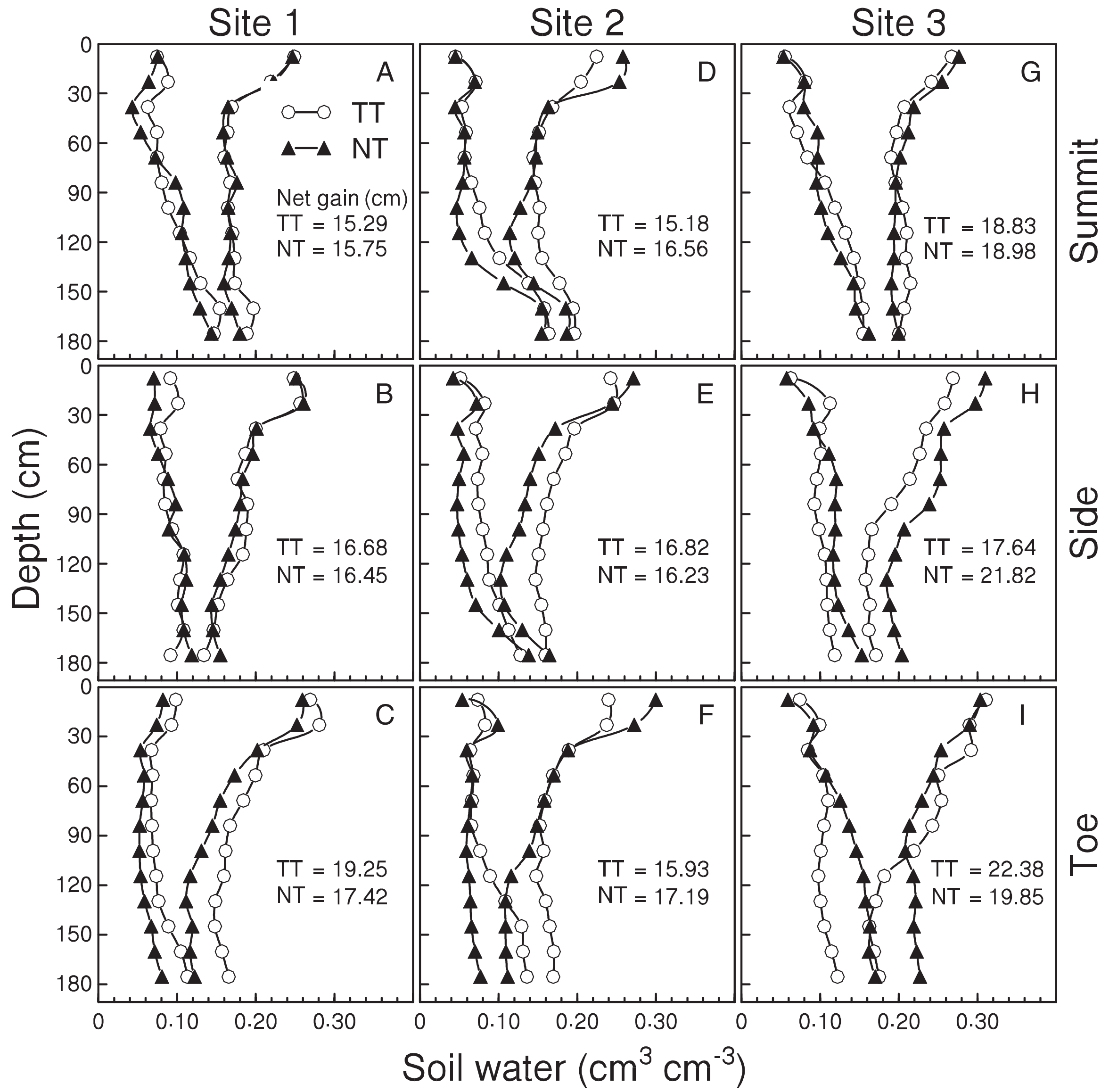

Fig. 3. Soil water distribution in the 180-cm profile with traditional-till (TT) and no-till (NT) just after wheat harvest in September (left pair of data lines) and again in early April (right pair of data lines) at three slope positions at three paired farm sites. Data are the average for 2 yr. Numerical values are the 2-yr average net gain in over-winter soil water for TT vs. NT at each slope position. Figures A, B, and C are the three slope positions for summit, side and toe for Site 1. Figures D, E, and F are the three slope positions for summit, side and toe for Site 2. Figures G, H, and I are the three slope positions for summit, side and toe for Site 3.

biomass with long-term NT was also reported by Holland and Coleman (1987) and Petersen et al. (2002). Drijber et al. (2000) found greater microbial biomass in NT, and Karlen et al. (1994) also reported an increase in DEA that was not evident in our study because of the higher pH in the TT soils.

Additional differences in soil parameters were observed and may also have been confounded by slope position. The slope-position effect may be confounded by the calcium carbonate layer. At the toe- and side-slope positions, NT had higher SOC than TT in the surface 0 to 5 cm (Fig. 1a). There were no differences in SOC between tillage treatments at the summit position, probably because of the eroded condition of the ridge tops that occurred before the adoption of NT. At the summit, few differences between TT and NT were seen in most analyses. There were no consistent differences in soil quality measurements across tillage when sites were compared with each other even though the sites varied in time under NT management.

Residue on the soil surface enhances soil water storage during the first stage of evaporation when the soil surface is wet (Lemon, 1956). Ramig and Ekin (1976) and Papendick (1987) showed that under Pacific Northwest conditions, over-winter soil water storage is directly related to quantity of wheat straw on the soil surface; the greater the quantity of straw, the more water is stored in the soil. The additional water retained by maintaining the stubble will increase the grain yield of the subsequent crop (Papendick and McCool, 1994). In our study, all tillage operations in TT were conducted in the spring; therefore, all fields had high quantities of undisturbed and standing wheat stubble throughout the winter.

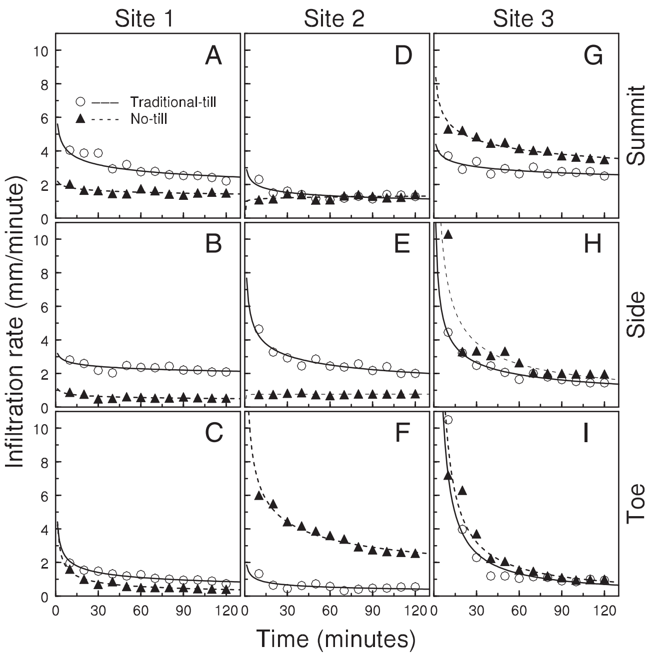

Fig. 4. Ponded water infiltration into traditional-till (TT) and no-till (NT) soil at three slope positions at three paired farm sites in September 2001. Measurements were obtained in standing and undisturbed wheat stubble. The quantity of water that had infiltrated into the soil was recorded at 10-min intervals during each 120-min run. Figures A, B, and C are the three slope positions for summit, side and toe for Site 1. Figures D, E, and F are the three slope positions for summit, side and toe for Site 2. Figures G, H, and I are the three slope positions for summit, side and toe for Site 3.

Our hypothesis was that during the transition from TT to NT, undisturbed capillary channels and pores as well as earthworm burrows would develop to enhance flow of water into the soil (i.e., decreased first-stage evaporation) that would improve soil water storage as described by Dao (1993) and Edwards et al. (1988). Why did we find no differences in either over-winter soil water storage or ponded water infiltration rate as affected by tillage in this study? Although numerous tillage operations were conducted in the TT treatment at all sites, the over-winter soil water storage and ponded water infiltration rate measurements were obtained after wheat harvest where soil had not been disturbed for at least 12 mo. at Sites 1 and 2 and at least 5 mo. at Site 3. Capillary pore continuity from the surface to below the tillage depth in TT fields was likely reestablished by vigorous and extensive growth of wheat roots during the crop growing season. Although middens and 4-mm wide vertical burrows created by surface-feeding night crawlers (*Lumbricus terrestris* L.) were observed on low-lying fields near Site 3 on the Aeschliman farm, only horizontal-burrowing *Apporectodea trapezoides* and related species of earthworms were present on slopes where the experiment was conducted (Fauci and Bezdicek, 2002). These earthworms are belowground feeders generally found in the surface 10 cm of soil (Wuest, 2001), and thus are unlikely to provide much benefit for water infiltration. Although frozen-soil water runoff did not occur during either of the mild winters of the study, over-winter soil water storage and ponded water infiltration rate data suggest that little or no differences in runoff could be expected if both TT and NT systems had similar quantities of standing wheat stubble. The significant differences in over-winter soil water storage as affected by slope position in our study were likely due to gravity flow of water as ponded water infiltration rate was not affected by slope position (Table 3).

Water erosion on Palouse cropland is largely caused by: (i) moldboard plowing in the fall before the onset of winter precipitation, or (ii) newly planted winter wheat on fields with inadequate surface residue, due to either excessive tillage to prepare the seedbed for winter wheat planting or following a low-residue-producing crop like spring pea (*Pisum sativum* L.) or spring lentil (*Lens culinaris* Medik). Thus, NT will provide year-long and season-to-season protection against water erosion whereas tillage-based systems, especially those involving moldboard plowing, are vulnerable to erosion at several stages.

The impact of TT vs. NT on soil parameters in the Palouse region was varied in this study. Differences in over-winter soil water storage were measured between sampling times, sites, and slope position, but were not as affected by tillage management. There were no differences in ponded water infiltration rate as affected by site, slope position, or tillage practice. Other soil quality measurements such as pH and DEA were more dependent on parent material, slope, and inherent soil properties than on tillage. The distribution of a calcium carbonate layer in side-slope position increased the pH in TT soils and resulted in a corresponding increase in DEA compared with NT. The differences in landscape that have occurred over thousands of years are greater than the effect of NT for the past 20 yr. The lack of differences in FAME profiles and DEA at the summit position between the two tillage treatments indicates that the erosion that occurred previous to NT adoption had a great effect on productivity and soil characteristics. However, some important changes did occur. Soil aggregation increased with NT management. Most importantly, SOC increased dramatically with NT, which illustrates the influences of lack of soil disturbance and residue retention on SOC accumulation. Changes in the microbial community were also evident between the two tillage treatments with a greater fungal component in NT. Summit-position cropland soils are the most highly eroded throughout the Palouse region and were the least impacted by NT in all parameters studied. Long-term studies on soil quality changes are needed to fully assess the impact of management on soil characteristics. In soil quality assessments, several aspects of the soil need to be considered as one or a few indicators are not sufficient to fully quantify changes that take place during the transition in soil management practices.

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